

# Physically Based Ultrasonic Feature Mapping for Anomaly Classification in Composite Materials

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## Abstract

Composite materials often contain anomalies that either come about during the fabrication process or develop during the service life of the structure. Some anomalies greatly reduce the strength of the material whereas others do not impose significant limitations on structural performance. Identification of these anomalies is often possible by employing ultrasonic feature mapping (F-map) techniques. In the F-map process, detection of anomalies is performed by observing

either a change in signal amplitude by traditional C-scan analysis, or by noting changes in the feature value of a back-wall echo or in a through-transmission signal. Identification is then accomplished by examining features that are developed by using physical models that describe the interaction between anomaly geometry and ultrasonic wave propagation. Photomicrographs are used in the development of a physical model and in the confirmation of anomaly type and definition. Identification procedures using the ultrasonic F-map process are presented for three common anomaly types. The F-maps and location results were generated with a color graphics terminal.

## INTRODUCTION

Composite materials are being used in primary structures in the aerospace and aircraft industries because of their high strength and modulus, dimensional stability, excellent fatigue resistance, notch insensitivity, and light weight. One of the major limitations of composite materials is the anomalies that are included during the fabrication process or that develop during the service life of the structure, thus reducing the structural performance. Other anomalies, in small sizes and quantities, do not impose significant limitations on structural performance. The relationship between anomalies and structural performance in composite materials is being studied at many research facilities.

### Review of Research

Many ultrasonic nondestructive testing (NDT) techniques have been examined for the detection of anomalies in composite materials. Rose and Shelton<sup>1</sup> in 1975 study the problem of damage analysis in composite materials where the extent of damage is analyzed with ultrasonic and radiographic techniques to find out how far fatigue damage, foreign-object damage, or environmental degradation extended into the composite structure. Results are obtained by noting changes in both the time signals and frequency spectra, although the results are mostly qualitative in nature, not quantitative, with respect to precise details of the anomaly characteristics as a result of the loading environment.

An interesting work is presented in 1977 by Kaelble and Dynes<sup>2</sup> where methods of detecting moisture degradation in a graphite-epoxy composite is studied. The key ultrasonic feature in this study for detecting moisture degradation is an analysis of wave velocity in the structure, while an acoustic attenuation measurement was evaluated for its potential in correlating with prior moisture history and strength degradation of the composite structure. This work points out the value of ultrasonic signal features, in this case using wave velocity and attenuation, to correlate with specific anomaly types in a composite structure.

Bar-Cohen, et al.<sup>3</sup> report a focused shock-wave pulse-echo technique that performs defect detection and characterization by direct comparison between a defect-free radio-frequency (RF) signal reference pattern and anomaly RF signals in a variety of composite sandwich structures. Judd and Wright<sup>4</sup> provide some very interesting explanations of void formation and their effects on the mechanical properties in a composite material, qualitative aspects of which have become useful in ultrasonic evaluation of the composite material structures. One interesting result in the paper indicates that the interlaminar shear strength of a composite would decrease by about 7 percent for each 1 percent void content up to a total void content of about 4 percent.

Reynolds and Wilkinson<sup>5</sup> make use of the anisotropic character of a composite material by measuring two or more ultrasonic wave velocities that can be correlated with fiber volume fraction and matrix porosity with reasonable accuracy. Tests reported by Vary and Lark<sup>6</sup> show the potential values of correlating ultrasonic stress wave factors with fiber composite tensile strength. In this study, an acousto-ultrasonic technique combines various characteristics of acoustic emission and low-frequency ultrasonics to develop this test procedure.

Characterization of composite materials has been performed using wave velocity and pulse spreading. Bar-Cohen, et al.,<sup>7</sup> make use of amplitude and velocity measurements obtained from an ultrasonic pulse-echo technique for characterizing a variety of intrinsic defects that could come about in the manufacturing process of filament winding and glass fiber-reinforced composite tubes. This study provides some model analysis and an estimation of signal feature variations as a result of the anomalies encountered by an ultrasonic wave in the composite structures. Sachse, et al.,<sup>8</sup> use the dispersive character of elastic wave propagation in a composite material to study moisture absorption and void content.

Williams and Lampert,<sup>9</sup> in 1980, use a through-thickness attenuation parameter to correlate with some impact-damaged composite material structures, again using particular signal features to identify a variety of problems in the composite structures. Wehrenberg<sup>10</sup> reviews the use of an acousto-ultrasonic technique for characterizing subtle defects in composite materials with reasonable success. Sendeky<sup>11</sup> performs a side-by-side comparison of a number of damage indications with enhanced x-radiography, through-transmission ultrasonic C-scan, and holographic NDT and describes some of the problems and virtues of the various NDT procedures. A complete review of the NDT of composite materials is reported by Scott and Scala,<sup>12</sup> and an explanation of actual application to aircraft structures is reported by Chang<sup>13</sup>. Also Matzkanin<sup>14</sup> describes the state of the art in ultrasonic and radiographic NDT of composite materials with a discussion on the degree of success associated with the procedures.

A paper by Rose, Jeong, and Avioli<sup>15</sup> points out the values of probability density function curves and also introduces the concept of feature mapping (F-map) in composite material inspection. The concept of inspectability is discussed in the paper. A variety of signal features are explored in detail for their uniform character, and variations throughout the entire composite material specimen are also examined. Some of the concepts presented in this paper are being extended today to F-map production so that investigators can understand defect types and the appropriate physical features associated with the anomaly type in the composite structure.

Continuing on with the use of different signal features, Bar-Cohen and Crane<sup>16</sup> report in 1982 the values of acoustic back-scattering of an ultrasonic wave in the Rayleigh region for the imaging of subcritical defects in the composite material. Teagle<sup>17</sup> reviews in 1983 the problem of the extreme anisotropy of a fiber-reinforced composite material and the corresponding ultrasonic velocity, attenuation, and frequency measurements that can be performed to characterize the mechanical structure.

In each of the references outlined above, a type of physical model of the defects or anomalies of interest is given so that an estimate can be made of some ultrasonic signal parameter variation as it travels through the structure.

### Feature Mapping

Feature mapping is a generalized approach to anomaly identification in composite materials that follows the feature-based methodology developed by Rose.<sup>18</sup> Selection of an inspection procedure (pulse-echo, through-transmission, etc.) and appropriate transducers are important initial steps in the learning process of anomaly classifications. Classification of anomalies is possible only if the ultrasonic signal contains the significant information needed to make discrimination possible.

A point-by-point scan over the suspected anomaly areas is performed, the entire ultrasonic signal being digitized and stored for further evaluation. Destructive testing or alternative NDT techniques are used to confirm the anomaly type and then to develop a physical model for signal analysis and anomaly-classification analysis. Features from the time and frequency domain are extracted and their utility evaluated with the use of probability density function curves. A classification algorithm is developed in strict accordance with the physical model of the anomalies. An F-map is then generated depicting the various anomaly types in a corresponding color code which allows the algorithm to be evaluated instantly. More information on the basis of composite material inspection and F-mapping can be found in Rose and Nestleroth.<sup>19</sup>

## EXPERIMENTS

To show the utility of anomaly identification in composite materials, two graphite-epoxy composite panels were inspected with a pulse-echo ultrasonic immersion scan followed by F-map analysis. The panels were constructed from graphite-epoxy

lamina, the first specimen having 8 plies and the second panel having 64 plies. The nominal ply thickness was 0.005 in. (0.127 mm), with the fiber direction of each oriented perpendicular to the fiber direction of the previous ply. The longitudinal wave velocity normal to the fiber orientation was 0.118 in./ $\mu$ s (0.30 cm/ $\mu$ s). Teflon® wafers, 0.50 by 0.50 by 0.005 in. (12.7 by 12.7 by 0.127 mm) were inserted between the plies at one quarter of the thickness, midplane, and three quarters of the thickness during the layup of the panel. Teflon wafers are often used to simulate inclusion or delamination anomalies. These foreign-object planar-inclusion anomalies served as the first type of anomaly for identification purposes in this study.

A second anomaly type consisted of multiple voids (porosity) in the matrix that formed during the manufacturing process of the composite. The third anomaly type was a true delamination, which is a separation of the interface between layers. This anomaly was formed by an impact load on a cured composite panel.

All three anomaly types were confirmed with photomicrographs along with an anomaly-free section of a composite, after completing the ultrasonic data-acquisition work. Figure 1a shows an anomaly-free composite specimen with the fibers appearing as white, the epoxy matrix as gray, and voids as black. Figure 1b shows the porosity as small black areas scattered in the fiber area. Figure 1c shows the delamination as a long, thin, black area in the center of the specimen. Figure 1d shows a cross section of the Teflon wafer foreign-object planar inclusion at the midplane of the specimen. Notice the excess epoxy directly above and below the wafer.

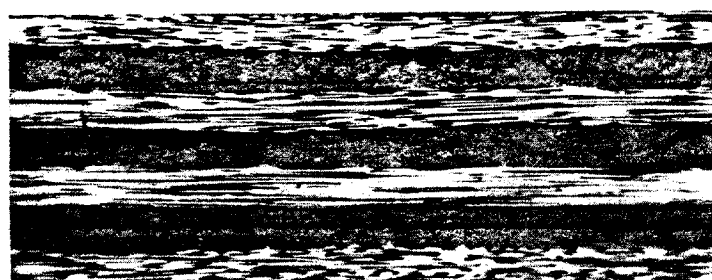
The ultrasonic test used in this experiment employed a pulse-echo, focused probe, immersion scan using longitudinal wave inspection. Pulse-echo testing is useful because depth determination and single-side inspection is possible. The reflected ultrasonic waveform from the front to the back wall echo is digitized and then stored on a disk for further evaluation with the F-map process. This scan consists of discrete points separated by 0.02 in. (0.51 mm) over the anomaly area. The transducer selected in this experiment was a 15 MHz broadbanded

focused probe. The pulse width at -12 dB is specified at 0.1  $\mu$ s and rings a total of 1.5 cycles. Using the velocity and distance for the material stated above, the separation of ply echos is 0.084  $\mu$ s, which is only slightly less than the pulse duration. The transducer bandwidth at -12 dB was nearly 20 MHz. The lateral resolution at -6 dB was 0.01 in. (125  $\mu$ m) and a measured focal distance of 1.4 in. (3.5 cm). Ultrasonic wave attenuation (27 dB/in. [11 dB/cm]) did not significantly affect the image of the 0.25 in.<sup>2</sup> (1.61 cm<sup>2</sup>) Teflon wafer at the 48th interface in the 64-ply composite.

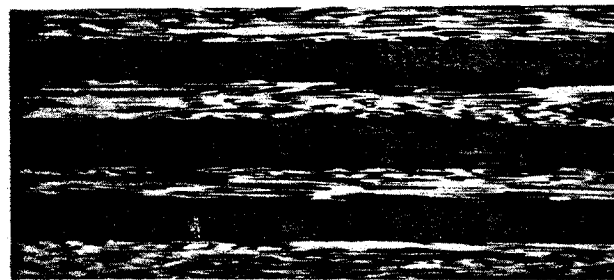
## RESULTS

In this section, sample F-map results illustrate the benefits and flexibilities available in anomaly detection and identification analysis. A color or gray-scale display can provide completeness in data analysis and interactive decision making in the F-mapping of composite materials because more than one recording threshold value can be examined in one graphical display. Before anomaly classification results are presented, a profile that presents both amplitude and arrival time information in one diagram is first examined. In traditional C-scan recordings, depth information is not precisely available, and only one recording threshold level for amplitude is possible.

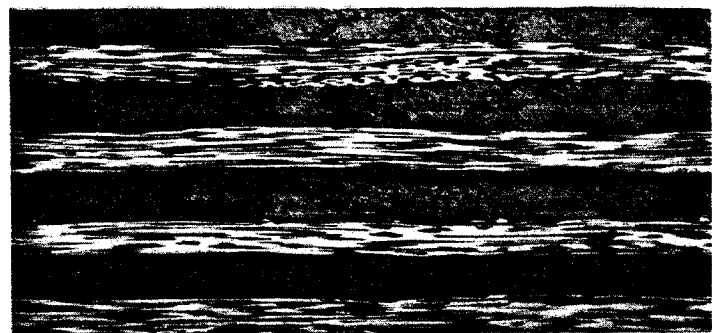
To demonstrate F-mapping, the 64-ply composite plate with the three Teflon inclusions at varying depths was scanned using a pulse-echo immersion test procedure. Both amplitude and depth features were extracted. Figure 2a shows the depths of the three Teflon inclusions as a function of color. The color intensity can be modulated as a function of amplitude to yield both a depth and C-scan map in one presentation, as shown in Figure 2b. The side view, Figure 2c, shows the depths for each of the inclusions. The color scheme for depth is arbitrary because depth does not directly translate to size and criticality of an anomaly. Spectral order is usually chosen, each depth being represented by a primary color. Because the reflected signal amplitude of the Teflon wafer is fairly uniform, the lightest color represents a 2 dB drop from the highest amplitude



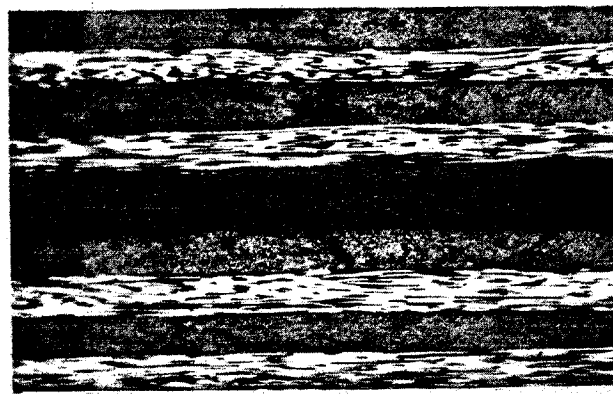
— 0.02 in. — A. ANOMALY-FREE



B. POROSITY



C. DELAMINATION



D. TEFLON INCLUSION

Figure 1—Sample photomicrograph for confirmation of anomaly type and development of physical models. The graphite

fibers are white, the epoxy matrix is gray, and any voids or inclusions are black.

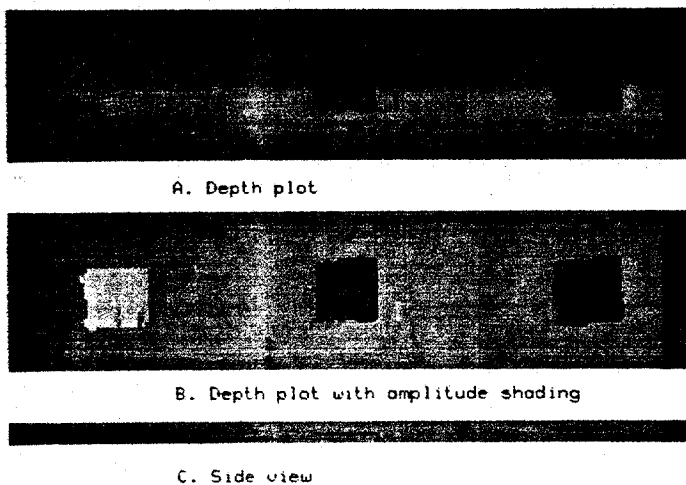


Figure 2—Color F-map showing defect depth as a function of color. Color shading can also be modulated as a function of amplitude to yield both a depth and C-scan map in one presentation.

(considered the reference) at that depth. This display technique compensates for the ultrasonic wave loss as it propagates through the composite material. The resolution of depth for this technique is two plies. This resolution could be reduced to one ply for thinner composites if additional signal-processing techniques were applied.

The most significant use of feature mapping associated with anomaly identification will now be presented using results for the 8-ply composite with the Teflon wafer foreign-object planar

inclusion, delamination, and porosities. A normal beam pulse-echo immersion test protocol was used in the study. A typical RF signal from a "good" composite material is shown in Figure 3a. Also shown is a gate set for detection of anomaly echoes occurring between the front-wall and back-wall echoes. Any reflected signal amplitude that exceeds a value of 25 percent of the front-wall echo would be examined for anomaly identification.

Physical models are constructed to anticipate an ultrasonic signal response that would be useful in describing the anomaly type. For porosity, individual volumetric character, and overall variations in position from one to another will cause the returning echo signal to be expanded because of a modified interference pattern due to the superposition of reflections with different arrival times. For porosities between consecutive interfaces, arrival time analysis indicates that the first half-cycle of the deeper porosity signal would superimpose on the third half-cycle of the closer porosity, causing a total increase in pulse length to 5 cycles, as shown in Figure 3b. The other two anomaly types, delamination and planar inclusion, are flat specular-like reflectors, which should return a signal with little arrival time variation in the components making up the final waveform. To separate these two anomaly types, the interface itself must be modeled. For the true delamination, the air backing constitutes a free boundary, and almost all of the ultrasonic energy will be reflected except possibly at small contact areas. For the Teflon inclusion, the high acoustical mismatch will cause a strong reflection. The layered media effect of the composite system including the Teflon and adhering interfaces, however, will cause a modification of pulse shape. Figure 3c shows a typical signal from the true delamination, which is very similar to the back-wall echo signal shown in Figure 3a. The signal from the Teflon inclusion is shown in Figure 3d.

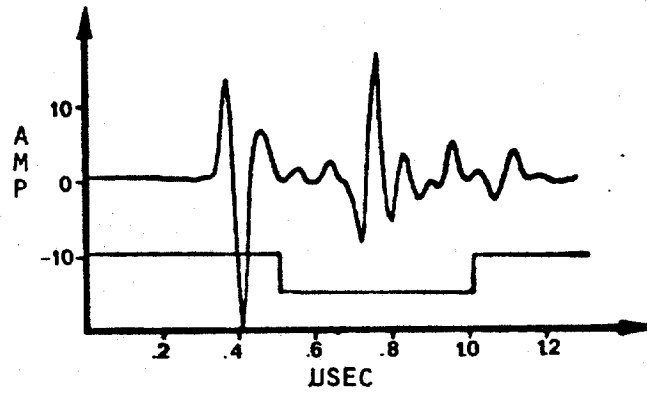
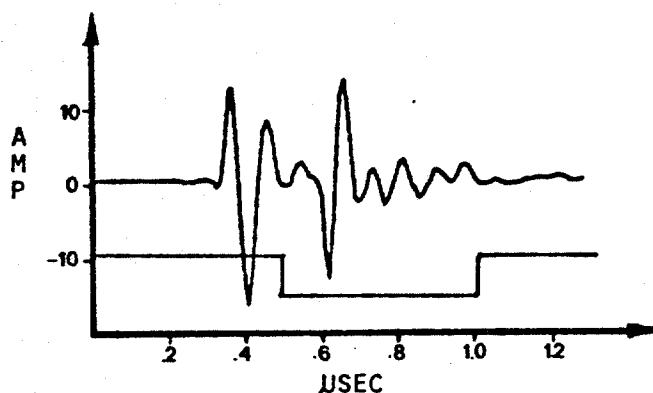
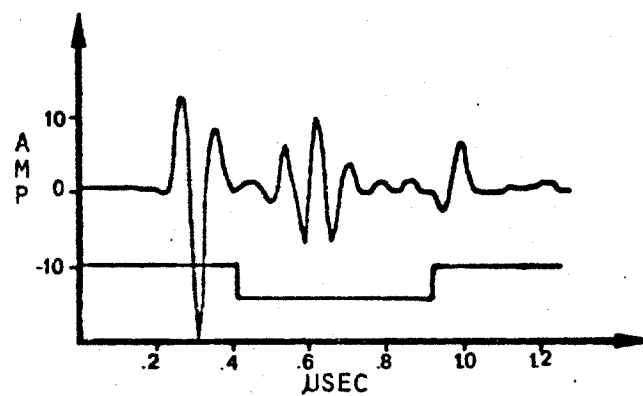
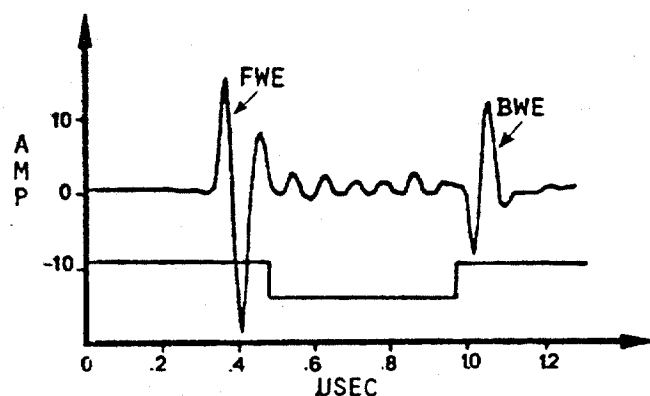


Figure 3—Sample RF signals from the 8-ply composite material. The front-wall echo (FWE) and back-wall echo (BWE)

are shown along with the gate used for anomaly detection.

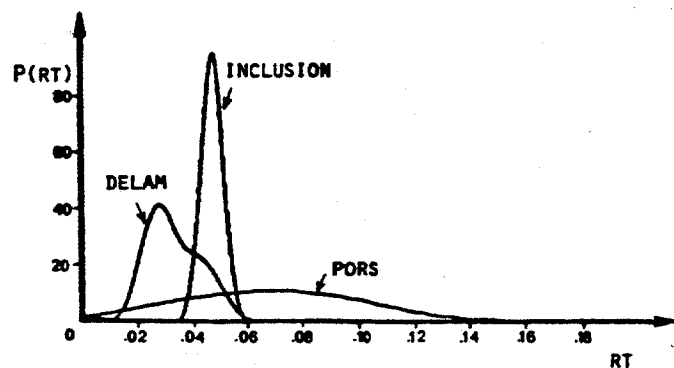
Feature selection and use in a classification algorithm for an anomaly classification scheme and for color selection in F-mapping is discussed next. Features selected for this four-class problem of planar inclusion vs. delamination vs. porosity vs. anomaly-free are given in Table 1. Amplitude is used for anomaly detection, while rise time, pulse duration, and stress reversal ratio are used in the classification. The value expectations for each of the anomaly types is shown in Table 2. These expectations were derived from the physical models presented earlier and confirmed by the probability density function (PDF) curves shown in Figure 4. A set of classification rules based on the intersection of the PDF curves were developed for anomaly identification and are presented in Table 3.

The success of the algorithm can be immediately evaluated by examining the color feature map in Figure 5. This figure shows a C-scan of the composite plate that was examined and the sections where anomaly classification was performed. The 2X magnification shows the Teflon-simulated delamination area in blue, the true delamination area in red, and the void area in green. Excellent agreement between the F-map results and the corresponding photomicrographs was obtained.

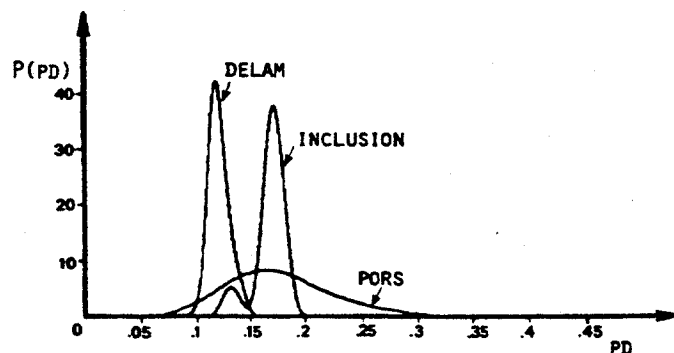
## CONCLUDING REMARKS

1. Success in this anomaly classification sample problem demonstrates the value of the F-map technique in composite material inspection. Classification of anomaly and defect type can lead to cost savings, prevention of catastrophic failure, increased service life, etc. The F-map process can now be extended to anomaly identification analysis in the many new composite material systems that are being developed today.

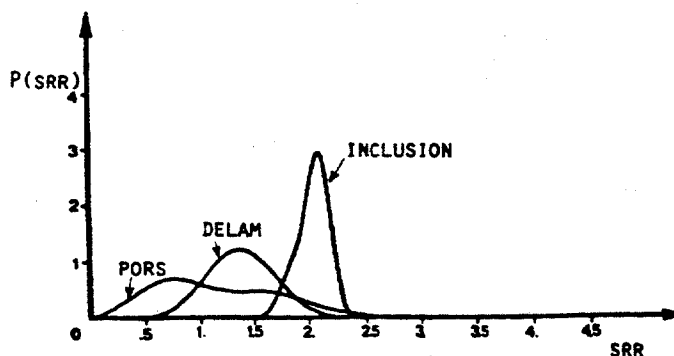
2. Fine tuning of a classification algorithm will always be necessary as material systems are changed or as a new group of anomaly geometrical characteristics are encountered. For example, in inclusion identification, modeled in this work by a Teflon insert of specific thickness, such geometrical parameters as inclusion thickness, shape change, or possibly a change in such material parameters as modulus or density could make an ultrasonic indication look different from what we might expect. On the other hand, changing the input frequency impinging on the anomaly will truly change the stress reversal ratio for some particular frequency if the reflector is indeed an inclusion. If the reflector is truly a delamination, however, no value of frequency will produce a stress reversal ratio that indicates an inclusion. The data-collection test protocol is hence modified to handle the fine tuning needed for examining different inclusion types. It is expected that only threshold values in classification algorithm will require adjustment as the ma-



A. PDF OF RISE TIME



B. PDF OF PULSE DURATION



C. PDF OF STRESS REVERSAL RATIO

Figure 4—Probability density function curves used in the algorithm development for identification of porosity (PORS), delamination (DELAM), and Teflon inclusions (INCLUSION).

TABLE 1 Features Selected for Anomaly Classification

Number	Name	Symbol	Description
1	Amplitude	AMP	25 percent of front-wall echo signifies detectable signal
2	Rise Time	RT	Time required for signal to rise from 25 to 90 percent
3	Pulse Duration	PD	Time required for signal to rise and fall, measured at 25 percent threshold
4	Stress Reversal Ratio	SRR	Magnitude of positive peak divided by magnitude of negative peak

TABLE 2 Expectation of Feature Tendencies for the Three Classes of Anomalies

Feature	Planar Inclusion	Delamination	Porosity
RT	Short	Short	Long
PD	Short	Short	Long
SRR	Large deviation from unity	Near unity	Large variation centered near unity

TABLE 3 Decision Rules for Anomaly Identification and Color Selection

Anomaly	Decision Rule	Color
Planar Inclusion	$RT < 0.06 \mu s$ and $SRR > 1.8$	Blue
Delamination	$RT < 0.06 \mu s$ , $SRR < 1.8$ , and $PD < 0.14$	Red
Porosity	$RT > 0.06 \mu s$ , or $SRR < 1.8$ and $PD > 0.14$	Green

terial system changes. The true test, however, of algorithm performance is based on prediction of anomaly type and evaluation by destructive micrographic assay.

3. The feature selection process for producing a meaningful anomaly-identification feature map is important. Best chances of success in anomaly-identification analysis are usually attained if the features considered are truly physically based. An estimate of the wave reflection signal characteristics from an anomaly is required to select properly suitable signal features, test frequencies, frequency bandwidths, numbers and locations of receiving transducers, etc., and then to have a good chance of identifying the anomaly.

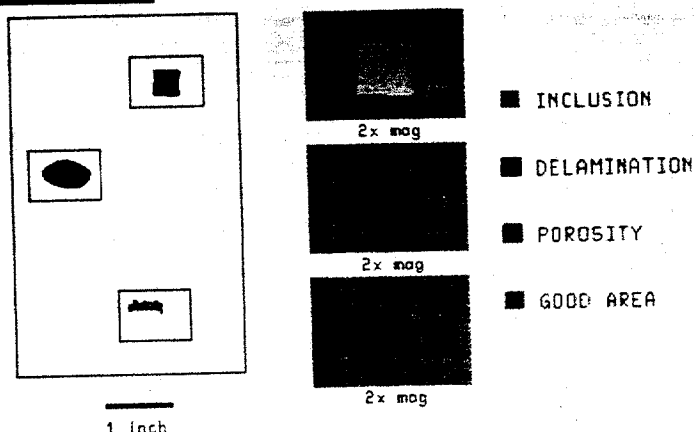


Figure 5—A C-scan (on left) is generated at a threshold of 25 percent of FWE used for the detection of anomalies. Color F-maps (on right) of the anomaly areas at 2X magnification are used for identification of anomaly types.

### Acknowledgment

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